

# AN OBSERVATIONAL SIGNATURE OF EVOLVED OCEANS ON EXTRA-SOLAR TERRESTRIAL PLANETS

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## ABSTRACT

The increase in luminosity with time of a main sequence star eventually can lead to substantial evaporation of the oceans on an orbiting terrestrial planet. Subsequently, the gas-phase  $\text{H}_2\text{O}$  in the planet's upper atmosphere can be photodissociated by stellar ultraviolet and the resulting atomic hydrogen then may be lost in a wind. This gaseous envelope may pass in front of the host star and produce transient, detectable ultraviolet absorption in the Lyman lines in systems older than 1 Gyr.

*Subject headings:* astrobiology – (stars): planetary systems

## 1. INTRODUCTION

The possible existence of life on other planets is of central interest in modern astronomy. A standard working hypothesis is that liquid water is required for life, and here we describe an observational signature of evolved oceans on extra-solar terrestrial planets.

The occultation of HD 209458 by a Jovian planet has demonstrated that it is possible to study the atmospheres of extra-solar planets with absorption line spectroscopy during a transit (Charbonneau et al. 2000, 2002). The Lyman  $\alpha$  spectrum of HD 209458 observed during its companion planet's transit can be explained as an outflow of hydrogen from this planet (Vidal-Madjar et al. 2003. Liang et al. 2003) that also has entrained other gases (Vidal-Madjar et al. 2004). Below, we describe an extension of this technique to study gaseous winds from terrestrial planets.

To date, only Jovian mass extra-solar planets have been detected. The discovery of terrestrial planets by occultations of their host stars is the goal of future space missions such as Kepler (see, for example, Jenkins 2002). In addition to transits discovered by photometry, it may be possible to perform transient absorption line spectroscopy to study gaseous outflows

from terrestrial planets, and we suggest that atomic hydrogen originating from evolved oceans might be detectable by this method. It seems likely that Venus once had oceans that were lost through a wind (Watson, Donahue & Walker 1981, Kasting & Pollock 1983), and computing the structure and composition of a gaseous outflow from an analog to Venus in orbit around a star with an age less than 1 Gyr is a goal of models being developed by Parkinson et al. (2003). However, as described below, the detection of an outflow from an Earth-like planet orbiting a star older than 1 Gyr is more promising.

Although not necessarily true in the past (see Sackmann & Boothroyd 2003), currently, the Sun’s luminosity is increasing with time (see Girardi et al. 2000). Eventually, if significantly vaporized,  $\text{H}_2\text{O}$  can dominate the composition of the Earth’s atmosphere since the total mass of the oceans is  $1.4 \times 10^{24}$  g while the total mass of the current atmosphere is  $5.1 \times 10^{21}$  g (Schubert & Walterscheid 2000). In approximately 1 Gyr, the Earth will be sufficiently warm that a “moist” greenhouse may occur and the temperature and composition profiles of the atmosphere will evolve so that the fraction of  $\text{H}_2\text{O}$  in the upper atmosphere is increased (Kasting 1988). When the Sun’s luminosity is 1.4 times its current value, or when its age is 8 Gyr (see Girardi et al. 2000), then depending upon the effects of clouds, a runaway greenhouse may occur and the oceans will be totally vaporized (Kasting 1988). As described by models for the early atmosphere of Venus, in the relatively water-rich upper atmosphere of the future, photodissociation of  $\text{H}_2\text{O}$  into OH and H (Ip 1983, Wu & Chen 1993) will be a major source of ultraviolet opacity. Subsequently, the resulting atomic hydrogen atoms may escape from the Earth in a wind. Below, we extend this scenario for the Earth’s future evolution to extra-solar terrestrial planets, and we argue that in some circumstances, the wind of atomic hydrogen from vaporizing oceans may produce observable absorption lines. The Earth now is losing about  $7 \times 10^{26}$  H atoms  $\text{s}^{-1}$  (see, for example, Pierrard 2003); we propose that this rate may increase by a factor of  $\sim 10^3$  in the future.

## 2. SCHEMATIC MODEL

Because there are many uncertainties and unknowns, we adopt a simple, schematic model. We assume oceans with  $9.3 \times 10^{46}$  H nuclei on an analog to the Earth in a circular orbit at a distance,  $D$ , from the host star. Once the planet is warm enough for a moist greenhouse to occur, much of the incident stellar ultraviolet is absorbed by water in the upper atmosphere. The photodissociated  $\text{H}_2\text{O}$  produces nonthermal hydrogen atoms with a typical speed of  $20 \text{ km s}^{-1}$  (Ip 1983, Wu & Chen 1993) which is greater than the escape velocity from the analog to the Earth of  $11 \text{ km s}^{-1}$ . However, because the density in the environment where these photodissociations occur is sufficiently high, there are multiple

collisions of the non-thermal hydrogen atoms with ambient matter and a hydrodynamic treatment of the outflow is appropriate.

Here, we use a simple scaling of the detailed calculations by Watson et al. (1981) and Kasting & Pollack (1983). The fluid outflow rate from the planet is largely determined by the heating in the uppermost atmosphere which is mainly composed of atomic hydrogen. If  $L_{EUV}$  is the star's luminosity in hydrogen-ionizing photons, then the net outflow of hydrogen atoms,  $\dot{Z}_H$ , is:

$$\dot{Z}_H \approx \epsilon_{wind} \frac{R_{pl}^2}{4 D^2} \frac{L_{EUV} R_{pl}}{G M_{pl} m_H} \quad (1)$$

where  $\epsilon_{wind}$  is the efficiency with which incident solar EUV photons are turned into heating the outflow,  $R_{pl}$  and  $M_{pl}$  and the radius and mass of the planet, and  $m_H$  is the mass of a hydrogen atom. For a region consisting largely of atomic hydrogen, we adopt  $\epsilon_{wind} = 0.3$  (Shull 1979, Kasting & Pollock 1983). Although it varies by at least a factor of 3 during a solar cycle (see, for example, Ayres 1997), a representative value for  $L_{EUV}$  is  $\sim 4 \times 10^{27}$  erg s<sup>-1</sup> (Judge, Solomon & Ayres 2003, Ayres 1997), thus yielding for an analog of the Earth that  $\dot{Z}_H = 5 \times 10^{29}$  s<sup>-1</sup>, coincidentally, a typical molecular loss rate from a bright comet at 1 AU (Whipple & Huebner 1976). Kasting & Pollack (1983) have computed detailed models for the evolution of water in an atmosphere around Venus. When the lower atmosphere is largely composed of H<sub>2</sub>O, their case D applies and the computed hydrogen mass loss rate is  $1.2 \times 10^{30}$  s<sup>-1</sup>. Using its radius, mass and distance from the Sun, we expect for Venus from equation (1) that  $\dot{Z}_H = 1.1 \times 10^{30}$  s<sup>-1</sup>, consistent with much more sophisticated calculations. We also note that with  $\dot{Z}_H = 5 \times 10^{29}$  s<sup>-1</sup>, the hydrogen wind persists for over  $\sim 5$  Gyr until the water-rich atmosphere produced by the vaporized oceans is largely depleted.

We now consider the detectability of this atomic hydrogen wind. We assume that the wind flows outward at constant speed,  $V$ , and that the atomic hydrogen is ionized with rate  $J_H$  (s<sup>-1</sup>). With the simplification of spherical symmetry, the density,  $n$ , as a function of distance,  $R$ , from the Earth is:

$$n(R) = \frac{\dot{Z}_H}{4\pi R^2 V} \exp\left(-\frac{R}{R_0}\right) \quad (2)$$

where  $R_0$  is a characteristic length (see, for example, Jura & Morris 1981) such that

$$R_0 = \frac{V}{J_H} \quad (3)$$

Scaling from the solar system, we adopt a photoionization rate of  $1.6 \times 10^{-7}$  s<sup>-1</sup> at  $D = 1$  AU (Ayres 1997) and, including charge exchange with stellar wind protons (Combi & Smythe 1988), a total hydrogen ionization rate at the Earth,  $J_0$ , of  $\sim 10^{-6}$  s<sup>-1</sup> or a mean lifetime for

neutral atoms of  $\sim 10^6$  s. A characteristic bulk outflow velocity of the hydrogen is  $1 \text{ km s}^{-1}$  (Kasting & Pollack 1983), but this value is uncertain and, as discussed below, perhaps too low. The characteristic sizes of a neutral hydrogen cloud around the terrestrial planet,  $R_0$ , are  $1 \times 10^{11} \text{ cm}$  ( $V = 1 \text{ km s}^{-1}$ ) and  $R_0 = 5 \times 10^{11} \text{ cm}$  ( $V = 5 \text{ km s}^{-1}$ ). In either case, the neutral hydrogen cloud is larger than the radius of the Sun ( $7 \times 10^{10} \text{ cm}$ ), and therefore, during an occultation, there can be detectable absorption by neutral hydrogen atoms.

Above, we assume that the gas flows radially away from the planet at constant speed and is unaffected by any external forces. In fact, radiation pressure by stellar Lyman  $\alpha$  can accelerate the gas with rate,  $a_H$  ( $\text{cm s}^{-2}$ ). If  $F_\alpha$  ( $\text{erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$ ) denotes the flux in the center of the stellar line, then using cgs units,

$$a_H = \left( \frac{F_\alpha}{m_H c} \right) \left( \frac{\pi e^2 f}{m_e c} \right) \quad (4)$$

where  $e$  is the charge of the electron,  $m_e$  the mass of an electron,  $c$  the speed of light, and  $f$  the oscillator strength of the absorption line (Spitzer 1978). Extrapolating from the solar system, at 1 AU,  $F_\alpha = 2.6 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$  (Combi & Smythe 1988), and the resulting acceleration of a hydrogen atom is  $0.6 \text{ cm s}^{-2}$  since  $f = 0.416$  (Wiese, Glennon & Smith 1966). If the atomic hydrogen cloud around the planet is optically thin in the core of the Lyman  $\alpha$  line, then during the mean lifetime of a neutral hydrogen atom in the wind, it would accelerate to  $6 \text{ km s}^{-1}$ . Because the gas is optically thick, the actual dynamical effects of the photons are complex. Here, because there are so many unknowns, we adopt the drastic simplification that the outflow around the terrestrial planet is spherically symmetric, and that the effect of radiation pressure from Lyman  $\alpha$  is that  $V = 5 \text{ km s}^{-1}$ . In our discussion of the observability of the wind, we present results both for  $V = 1 \text{ km s}^{-1}$  and  $V = 5 \text{ km s}^{-1}$ .

With an estimate of the structure of the neutral hydrogen cloud, we can now compute the strength and profile of the hydrogen absorption lines. If the cloud is larger than the star, then at the moment when the occulting planet lies in front of the center of the orbited star of radius  $R_*$ , the column density at the limb of the star,  $N(H)$ , is:

$$N(H) \approx \frac{\dot{Z}_H}{4 R_* V} \quad (5)$$

With  $R_* = R_\odot$ ,  $\dot{Z}_H = 5 \times 10^{29} \text{ s}^{-1}$  and  $V = 1 \text{ km s}^{-1}$  or  $5 \text{ km s}^{-1}$ , then  $N(H) = 1.8 \times 10^{13} \text{ cm}^{-2}$  or  $3.6 \times 10^{12} \text{ cm}^{-2}$ , respectively. Assuming a Gaussian line profile with a width characterized by  $\Delta\nu_0$ , the optical depth at line center of an absorption line,  $\tau(0)$ , is

$$\tau(0) = \frac{\pi e^2}{mc} f \frac{N(H)}{\sqrt{\pi} \Delta\nu_0} \quad (6)$$

For Lyman  $\alpha$ , we assume Gaussian line profiles with  $\Delta\nu_0 = 8.23 \times 10^9$  Hz and  $\Delta\nu_0 = 4.11 \times 10^{10}$  Hz, corresponding to  $1 \text{ km s}^{-1}$  and  $5 \text{ km s}^{-1}$ , respectively. With the column densities given above then  $\tau(0) \approx 14$  ( $V = 1 \text{ km s}^{-1}$ ) and  $\tau(0) \approx 0.5$  ( $V = 5 \text{ km s}^{-1}$ ). As discussed below, such lines are detectable if the velocity shift of the star is sufficiently different from that of the interstellar matter in the line-of-sight. Higher order Lyman lines in the circumstellar gas might be detectable even if observations at the stellar Lyman  $\alpha$  velocity are dominated by intervening interstellar absorption. We also note that the absorption lines produced by the wind from the planet are likely to be narrower than any structure in the the Lyman emission lines that are produced in the chromospheres of main sequence G-type (Combi & Smythe 1988, Redfield et al. 2002) where the gas temperature is typically greater than 10,000 K and even the thermal width of the hydrogen emission is greater than  $10 \text{ km s}^{-1}$ .

We now consider how different levels of stellar activity can affect the observability of the planet’s wind. The mass loss rate of hydrogen from the planet ( $\dot{Z}_H$ ) scales with  $L_{EUV}$  and thus there is a tendency for more active stars to drive a stronger planetary wind and produce a larger projected column density of hydrogen. However, an increase in the stellar activity also leads to an increase in the neutral hydrogen ionization rate ( $J_H$ ) and thus a decrease in the size of the neutral cloud around the planet ( $R_0$ ). To assess these combined affects, we compute the value of the equivalent width of an absorption averaged over the disk of the star when the planet lies toward the very center of the star. We ignore any limb brightening or darkening of the stellar atmosphere. Because there are so many uncertainties, we consider Doppler broadening parameters equal to the assumed outflow speeds of either  $1 \text{ km s}^{-1}$  or  $5 \text{ km s}^{-1}$ . Considering main sequence stars of age,  $t_*$ , and following Ayres’ (1997) study of photo-ionization rates and Wood et al.’s (2002a) study of stellar winds, we assume that both  $J_H$  and  $L_{EUV}$  scale as  $t_*^{-2}$ .

We show in Figures 1 and 2 plots of  $W_\lambda$  for the first three lines in the Lyman series vs.  $J_H/J_0$ . For both  $V = 1 \text{ km s}^{-1}$  and  $V = 5 \text{ km s}^{-1}$ , we see that for  $J_H/J_0 \sim 1$ , the predicted line strengths can be larger than  $5 \text{ m}\text{\AA}$  and therefore can be measured either with the Hubble Space Telescope or, possibly, with the Far Ultraviolet Spectroscopic Explorer (see, for example, Meyer, Jura & Cardelli 1998, Wood et al. 2002b). We also see that for  $J_H/J_0 > \sim 20$ , which occurs when the star is younger than 1 Gyr, the ionization rate of atomic hydrogen is so rapid that the outflowing neutral cloud no longer effectively covers much of image of the star and the predicted equivalent widths decrease significantly. This result suggests that it will be difficult to use Lyman line absorptions to detect evaporated oceans around stars younger than 1 Gyr. Also, if  $J_H/J_0 \ll 1$ , the absorption lines are weak because not much atomic hydrogen is being lost from the planet.

### 3. DISCUSSION

We now consider observational strategies to find this signature of evolved oceans. The probability that a star is transited by a planetary wind of characteristic size,  $R_0$ , is approximately  $R_0/D$ , which, for an analog to the Earth in orbit around a Sun-like main sequence star, is  $\sim 7 \times 10^{-3}$  for  $V = 1 \text{ km s}^{-1}$  and  $\sim 3 \times 10^{-2}$  for  $V = 5 \text{ km s}^{-1}$ . If the hydrogen-rich wind has a duration of 5 Gyr, and the main sequence lifetime of the orbited star is about 10 Gyr, then there is a probability of 0.5 of observing the system during an era when the planet has a detectable outflow. Since the local density of G-type main sequence stars is about  $0.003 \text{ pc}^{-3}$  (see, for example, Greaves & Wyatt 2003), then, depending upon the unknown fraction of these stars that possess suitable planets, a main sequence G-type star that displays the transient hydrogen absorption may lie within  $\sim 25 \text{ pc}$  of the Sun. Such stars are inside the local interstellar bubble and therefore the column of atomic hydrogen is typically less than  $10^{19} \text{ cm}^{-2}$  (Lehner et al. 2002). In order to detect the transient hydrogen lines during an occultation, the radial velocity of the star must be sufficiently different from the interstellar velocity that the optical depth in the damping wings of the interstellar hydrogen line is less than unity. For a column density of  $10^{19} \text{ cm}^{-2}$ , the required velocity offsets are  $160 \text{ km s}^{-1}$ ,  $33 \text{ km s}^{-1}$  and  $12 \text{ km s}^{-1}$  for Lyman  $\alpha$ , Lyman  $\beta$  and Lyman  $\gamma$ , respectively. Since the typical velocity dispersion of the G type stars in the solar neighborhood is  $20 \text{ km s}^{-1}$ , for most stars with transiting planets, it should be possible to detect the associated transient circumstellar hydrogen absorption in Lyman  $\gamma$ . Stars with lower column densities of interstellar matter and/or stars with somewhat higher than average radial velocity may be suitable for observing at Lyman  $\beta$  or, in the most favorable cases, Lyman  $\alpha$ .

When a terrestrial planet is found to occult a main sequence star, it should be possible to infer from its period the distance of the planet from the star and therefore the planet's surface temperature and the amount of water that might have been evaporated. Evolved oceans would be the most likely source of any sustained, substantial outflow of hydrogen from an extra-solar terrestrial planet.

Our model of a hydrogen-rich wind can be tested. (i) The measured mass outflow rate in the hydrogen-rich wind,  $\dot{Z}_H$ , can be compared with the prediction from equation (1) after measuring the star's X-ray emission. (ii) By observing the amount of hydrogen absorption before and after the star's occultation by the disk of the planet, it should be possible to test the characteristic spatial extent of the neutral gas,  $R_0$ , predicted by equation (2). To be exact, it will be necessary to measure  $V$  which can be done either directly from the line profile or indirectly from the curve of growth. (iii) It may be possible to detect species besides hydrogen in the outflow. For example, in the Earth's oceans,  $[D]/[H] = 1.6 \times 10^{-4}$ , about an order of magnitude greater than  $[D]/[H]$  within the interstellar medium. In a planetary

wind, some deuterium is entrained with the outflowing hydrogen (see Keating & Pollack 1983), and a  $[D]/[H]$  ratio significantly in excess of the interstellar value could be another signature of an evolving ocean. However, in our model, the predicted equivalent width of the deuterium Lyman  $\alpha$  line is  $< 0.1 \text{ m}\text{\AA}$  and therefore very difficult to detect.

#### 4. CONCLUSIONS

The oceans on a terrestrial planet may store the bulk of its hydrogen. When the host star’s luminosity increases enough so that the oceans are substantially evaporated, a wind of atomic hydrogen from the planet could be strong enough to produce detectable transient Lyman absorption lines in the star’s ultraviolet spectrum. Systems older than 1 Gyr are particularly promising candidates to exhibit this signature of terrestrial planets with evolved oceans.

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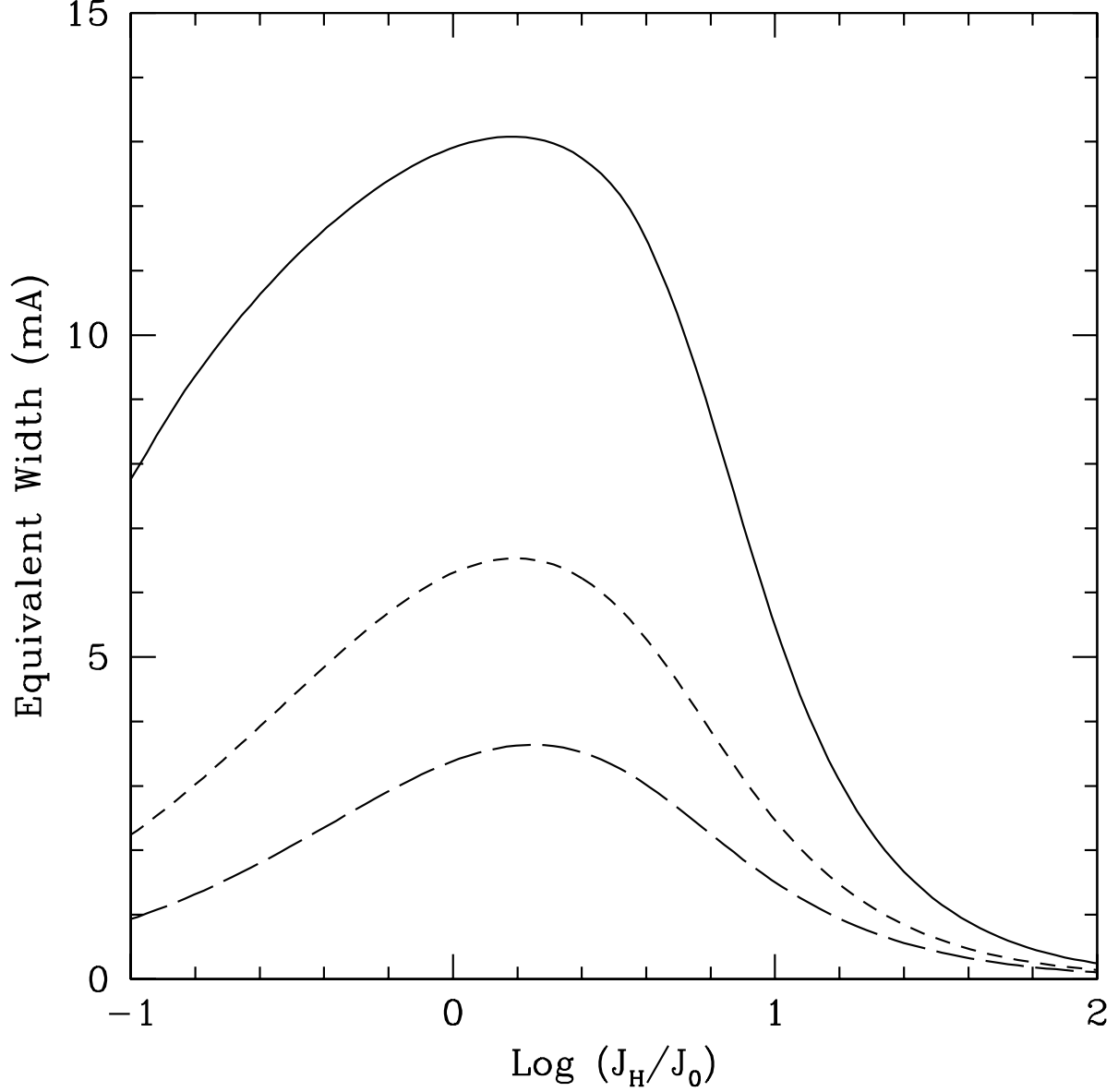


Fig. 1.— Using the model described in the text, we show a plot of the predicted equivalent width of Lyman  $\alpha$  (solid line), Lyman  $\beta$  (short-dashed line) and Lyman  $\gamma$  (long-dashed line) for different values of the relative hydrogen ionization rate,  $J_H/J_0$ . As described in the text, we assume that  $L_{EUV}$  scales as  $J_H$ . For these curves we assume an outflow velocity and a Doppler broadening parameter both equal to  $1 \text{ km s}^{-1}$ .

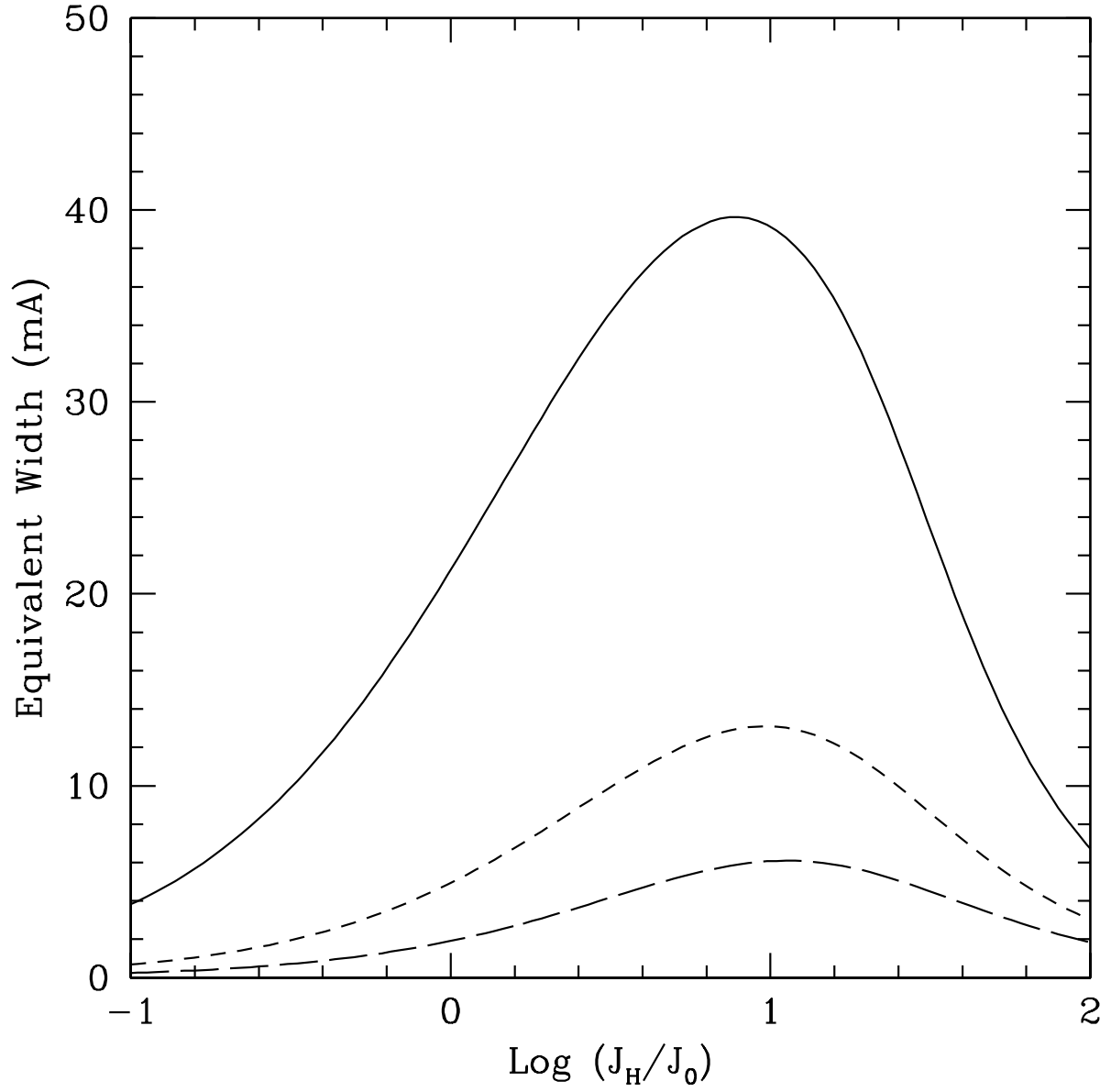


Fig. 2.— The same as Figure 1 except that we assume an outflow velocity and a Doppler broadening parameter both equal to 5 km s<sup>-1</sup>.